Development in the DIII-D Tokamak of Hybrid Operation Scenarios for Burning Plasma Experiments*

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Stationary discharges with $q_{95} \geq 4$ which extrapolate to high fluence operation in burning plasma experiments such as ITER ("hybrid operation") have been reproducibly obtained in the DIII–D tokamak. While it is difficult to charactize the relative fusion performance of various discharges by a single dimensionless parameter, one useful measure is the fusion gain parameter $\beta_N H_{89}/q_{95}^2$. Standard scenario [$q_{95} = 3$, ELMing H–mode] performance for Q = 10 operation in ITER is projected to have $\beta_N H_{89}/q_{95}^2 = 0.42$. Discharges with $\beta_N H_{89}/q_{95}^2 = 0.39$ have been maintained in DIII–D for >6 s which is >30 τ_E and >2 τ_R (current profile relaxation time). Discharges of shorter duration have been operated up to the estimated no-wall β limit with $\beta_N H_{89}/q_{95}^2 = 0.43$, limited by technical constraints, not loss of performance.

The key to this high performance regime is the relaxation of the current profile to a stationary state without sawteeth. The reconstructed q profiles have $q_{min} = q(0) \simeq$ 1.05–1.1. Estimates of the expected current profile indicate it should be slightly more peaked with $q(0) < 1.0$. A small 3/2 tearing mode appears to play a key role in maintaining $q(0) > 1$. The tearing mode appears as an off-axis voltage source which broadens the current profile. Deterministic means of broadening the profile, such as off-axis ECCD,may also be feasible. With no sawteeth, β can be raised to the no-wall β limit without large tearing modes. Discharges have been operated with β_N above 90% of the estimated no-wall β limit ($4\ \ell_i$) for >1 s. A fiducial discharge with $q_{95} = 3.1$ and sawteeth encounters a disruptive 2/1 tearing mode at 75% of the no-wall β limit.

Hybrid operation at higher q_{95} leads to reduced flux consumption. Estimates for ITER indicate 4000 s discharges would be possible with the present central solenoid design flux. In addition, the reduced current would lessen the potential for harmful effects from a major disruption. Projections to ITER at constant β_N and confinement multiplier (various scalings) have been made. For Bohm scaling with plasma size (ITER89P), the discharges project to Q = 7.6 at $\beta_N = 2.8$. With gyroBohm scaling, the discharges project to ignition with a 20% confinement margin. The work in the present DIII–D experimental campaign will focus on demonstrating the robustness of this scenario by mapping the existence and performance in the q_{95} and collisionality space. These experiments will be carried out in cooperation with the ITPA topical groups on steady-state operation and ITBs.

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